

PCT

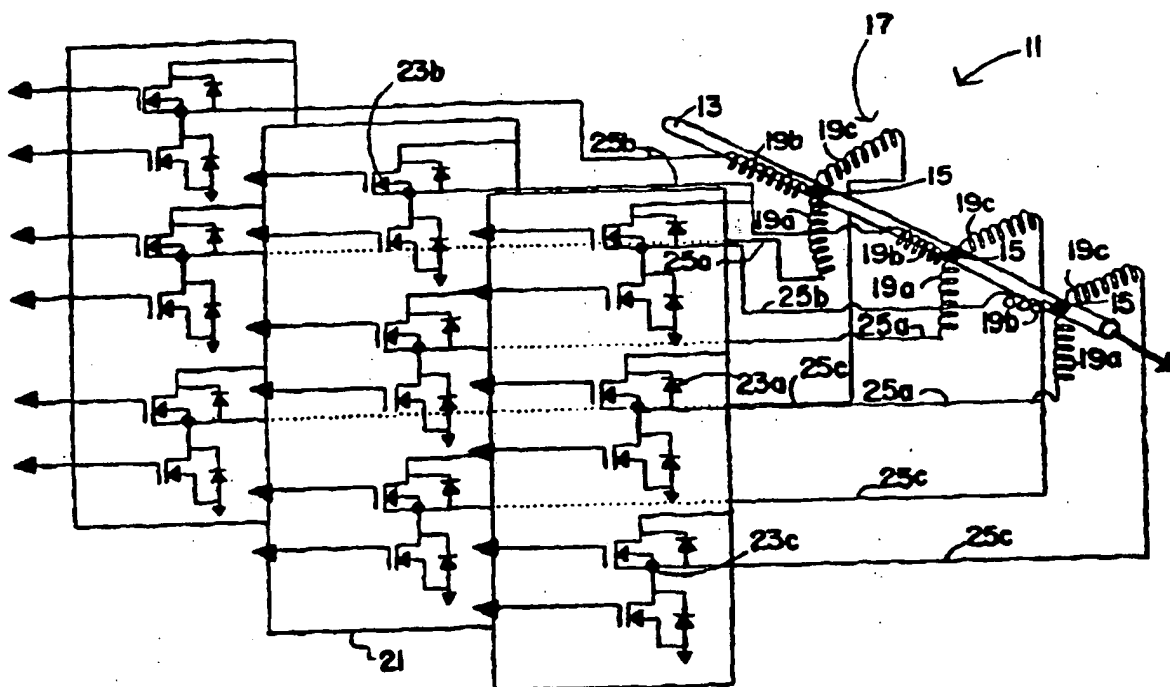
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<p>(21) International Application Number: PCT/US93/11956 (22) International Filing Date: 9 December 1993 (09.12.93) (30) Priority Data: 07/992,242 14 December 1992 (14.12.92) US (71) Applicant: HONEYWELL INC. [US/US]; Honeywell Plaza, Minneapolis, MN 55408 (US). (72) Inventors: HOEL, Robert, H.; 5401 40th Avenue North, St. Petersburg, FL 33709 (US). ZUBKOW, Zygmunt; 111 Rodney Court, Palm Harbor, FL 34684 (US). (74) Agent: GEBHARDT, Mark, J.; Honeywell Inc., Honeywell Plaza-MN12-8251, Minneapolis, MN 55408 (US).</p>		<p>(81) Designated States: JP, RU, European patent (AT, BE, CH, DE, DK, ES, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE).  Published With international search report. Before the expiration of the time limit for amending the claims and to be republished in the event of the receipt of amendments.</p>

(54) Title: MOTOR SYSTEM WITH INDIVIDUALLY CONTROLLED REDUNDANT WINDINGS



(57) Abstract

A fault tolerant brushless DC motor includes plural parallel windings (17), each individually controlled by a respective control module (21). At least three windings are provided such that in the event there is a short in one of the windings, the other two windings continue to generate a field to cause the shaft (13) of the motor, having permanent magnets (15) mounted thereon, to rotate. Preferably at least three windings (17) are provided such that in the event of a single short, one of the remaining two windings serves to nullify the drag generated by the shorted winding with the other remaining winding generating a sufficient field to cause the shaft (13) of the motor to rotate. The motor system has particular application in a field of vector control of rocket nozzles. In a preferred configuration, the system includes eight windings (17).

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## MOTOR SYSTEM WITH INDIVIDUALLY CONTROLLED REDUNDANT WINDINGS

### FIELD OF THE INVENTION

5 This invention relates generally to brushless DC motor systems. In particular, the invention relates to a brushless DC motor system especially adapted for use in high reliability uses where redundancy is essential, such as in thrust vector control of rocket engines.

### BACKGROUND OF THE INVENTION

10 Thrust vector control of rocket engines has in the past been primarily accomplished with the use of hydraulic actuators. Hydraulic actuators employing hydraulic pumps, while commonly in use, have a disadvantage in that they require high-maintenance costs and suffer from low reliability. More particularly, hydraulic pumps  
15 typically run at full speed thereby requiring operation of the hydraulic system controlling the rocket engine to operate at continuous maximum power. Other disadvantages include the fact that they require use of dangerous materials such as hydrazine and are generally very messy due to the presence of hydraulic fluid over the parts.

20 Alternative approaches to hydraulic actuators have involved the use of electromagnetic actuators. In comparison to hydraulic systems, electromagnetic actuator systems use much less energy, with a typical hydraulic actuator system using over 34 times as much energy during a mission as a comparable electromagnetic actuator system. Other advantages resulting from the use of electromagnetic actuator  
25 systems is that they are very rugged and require low maintenance. Further, installation of such devices is extremely simple and testing of such systems can be accomplished prior to launch of a rocket using either external or internal battery power. In this regard, the past three basic approaches for motors in electromagnetic actuator systems used in rocket nozzle control have been considered. Specifically, the systems considered in the  
30 past are "switched reluctance", "AC induction" and "DC brushless motors".

DC brushless motors are available in several configurations from open loop controlled multi-toothed propelled drives called stepping motors to inside permanent magnet rotor and outside permanent magnet rotor closed loop machines. Due to their wide range of performance and motion control capabilities, such motors are  
35 theoretically particularly desirable for use in applications such as rocket vector control, for example, in controlling the direction of orientation of rocket motor nozzles. However, such motors have not been used widely in the field of rocket nozzle control because in the event of shorting of the winding of the motor, the system could

experience a catastrophic failure due to the inability to move the DC brushless motor, which locks up upon the shorting of a winding. As may be appreciated, such a failure in the motor can result in a complete and catastrophic failure of the rocket mission.

Thus, to date, as an alternative to the above noted hydraulic systems, there has been proposed the use of AC induction motors. Such systems are desirable in that AC induction motors will typically not lock up upon the shorting of a winding, but have the disadvantages that AC induction motor control electronics are highly complex and the torque/speed characteristics of such motors vary greatly and do not provide the precise control desired for rocket nozzles.

Accordingly, in accordance with the invention, there is proposed a DC brushless motor system which suffers none of the disadvantages of hydraulic and AC motor systems while overcoming the previously recognized catastrophic failure possibilities. More particularly, there is disclosed herein a DC brushless motor system which is fault tolerant to windings shorting when in operation.

#### SUMMARY OF THE INVENTION

In accordance with one aspect of the invention there is provided a permanent magnet motor system. The permanent magnet motor system includes a shaft for having multiple permanent magnets mounted thereon, and with the shaft rotatably mounted for rotation about a central axis thereof. The permanent magnets are mounted along a predetermined length of the shaft, substantially around the circumference thereof, for causing the shaft to rotate as a result of an inductive force being applied to the permanent magnets. At least three windings, each electrically isolated from each other, are arranged around the permanent magnets, each for being individually electrically excited to generate an induction field. The field generated causes the shaft to rotate as a result of the interaction between the generated field and the permanent magnets. Individual winding controllers, for example, pulse width modulation controller chips, individually control each of the windings in a manner such that should there be a short in one of the windings, the other two windings continue to generate the necessary fields to (1) continue to drive the shaft in a rotational motion, and (2) overcome the drag created by the shorted winding. Thus, the motor system is fault tolerant taking into account, in a DC brushless motor arrangement, the possible shorting of a winding thereof.

The windings are preferably arranged in a Y-winding configuration with each of the winding legs parallel to the others. Such a configuration is conventional and well known to those of ordinary skill in the art. Preferably, the winding controllers are insulated gate bipolar transistor power modules. In a preferred arrangement, the windings comprise at least three windings and more preferably, at least eight. As may

be appreciated, in the case with eight windings, should one winding short, the motor will still retain 3/4 of its power due to the loss of one winding by shorting, and another winding being dedicated to overcoming the drag of the winding that shorted. In the case of a single winding shorting in a three winding arrangement, 1/3 power is retained.

5 In a more specific aspect of the invention, a sensor or sensors are arranged for detecting the rotational position of the shaft. The sensor or sensors provide a signal to a motor controller, which controls the insulated gate bipolar transistor power modules of the windings, to issue a control signal to the power modules to excite the windings to cause the shaft to be rotated into a desired position.

10 These and other features and advantages of the invention will be more readily apparent upon reading the following detailed description of the invention, made with reference to the accompanying drawings.

### **BRIEF DESCRIPTION OF THE DRAWINGS**

15 Figure 1 is a schematic diagram of the control circuit architecture and winding arrangement for a DC brushless motor system in accordance with the invention; and

Figure 2 is a second schematic diagram showing the control modules of Figure 1 connected to a motor controller, and with the motor shaft having a position sensor thereon.

### **DETAILED DISCUSSION**

20 Referring to Figure 1, the fault tolerant winding control system, in accordance with the invention, is designated generally by the reference number 11. A single common shaft 13 is shown illustrated in association with redundant windings 17 arranged in a Y configuration about the shaft. The shaft 13 includes permanent magnets 15 mounted about the length thereof and about the circumference of the shaft 13. The windings 17 are connected in a manner to be individually and separately electrically excited to generate a field which interacts with the magnets to cause the shaft 13 to rotate. Each winding 17 has three legs, 19a, 19b, and 19c, which are arranged in a conventional and well known Y configuration.

25 In Figure 1, each winding 17 is shown individually controlled by a respective control module 21. These modules 21 are, for example, insulated gate bipolar transistor power modules. Thus, should a winding 17 be shorted, the other redundant windings 17, which are each individually and separately controlled by the power modules 21 through insulated gate bipolar transistors 23a, 23b and 23c, continue to drive the shaft 13 of the motor.

35 As may be appreciated, in order to achieve fault tolerant operation, there should be at least three windings 17, and preferably eight (as generally designated by the solid

arrow showing an extension of shaft 13). Thus, the loss of one winding 17 due to shorting, in the case of three, results in a motor having at least 1/3 of its original drive power, and in the case of eight windings, a loss of only 1/4 of its power.

5 With respect to the modules 21, they are conventional and well known to those of ordinary skill in the art. Examples of such commercially available modules include the PWR-82331 high current three-phase bridge power hybrid. Details of such a module are disclosed in the publication by ILC Data Device Corporation PWR-282331 Smart Power Three-Phase Bridge, 1989, which disclosure is incorporated by reference herein.

10 To control the power modules 21 such that they are synchronized to ensure that the magnets are acted upon by the fields generated by individual windings 17 in a synchronized manner, a motor controller 27 is employed. Such a controller 27 is conventional and well known and can take the form of, for example, a programmable logic array (PLA).

15 As shown in Figure 2, to ensure more precise operation of the motor, position sensors 29 can be mounted on the shaft 13 to detect the position of the shaft 13 relative to where it has been commanded by motor controller 27 to be located. In such a case, the position detection sensors 29 provide a position signal to motor controller 27 wherein it is compared to a reference to result in an error signal. The error signal is then  
20 processed by the controller 27 to generate a signal to the control modules 21 to cause the shaft 19 to be rotated to the desired position correcting for the error until the error signal generated is equal to null.

25 Modification and variations of the present invention are possible in light of the above teachings. It is therefore understood that within the scope of the appended claims, the invention may be practiced other than as specifically described.

What is claimed is:

1. A brushless DC motor system, comprising:  
a single shaft rotatably mounted for rotation about a central axis thereof;  
a plurality of permanent magnets mounted along a length of and  
substantially about the circumference of said single shaft;  
at least three individually electrically excitable windings, said at least  
three windings for generating an induction field for interaction  
with said plurality of permanent magnets to cause said single  
shaft to rotate about said central axis, each winding individually  
electrically isolated from the other windings; and  
at least three synchronized individual control means, each individual  
control means connected to a corresponding winding of said at  
least three individually electrically excitable windings, said at  
least three synchronized individual control means for  
synchronized individual control of said corresponding windings  
such that each corresponding winding generates an induction field  
in a synchronized manner.
2. A system according to claim 1, wherein each of said at least three  
individually electrically excitable windings are arranged in a y configuration, and  
wherein each of said at least three synchronized individual control means include at  
least three insulated gate bipolar transistor power modules.
3. A system according to claim 1, wherein said at least three individually  
electrically excitable windings include eight sets of windings, each set arranged in a y  
configuration, and wherein said at least three synchronized control means includes eight  
insulated gate bipolar transistor power modules.
4. A system according to claim 1, further comprising:  
position detecting means for detecting the rotational position of said  
single shaft and generating a signal indicative of said rotational  
position; and  
motor controller means for receiving said signal indicative of said  
rotational position and for generating a control signal to said at  
least three synchronized individual control means for exciting  
said at least three windings to cause said single shaft to rotate to a  
desired rotational position.

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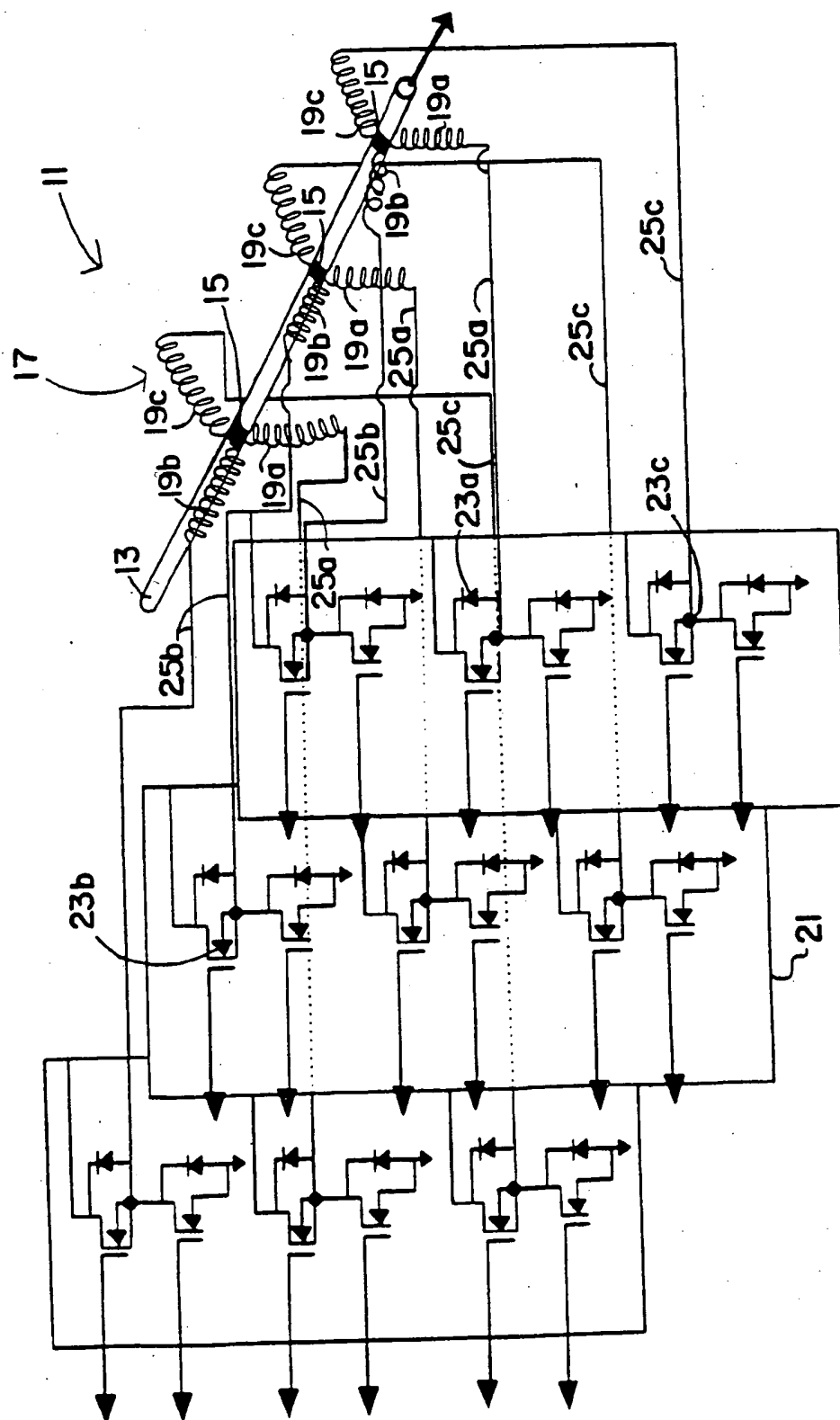


FIG. 1



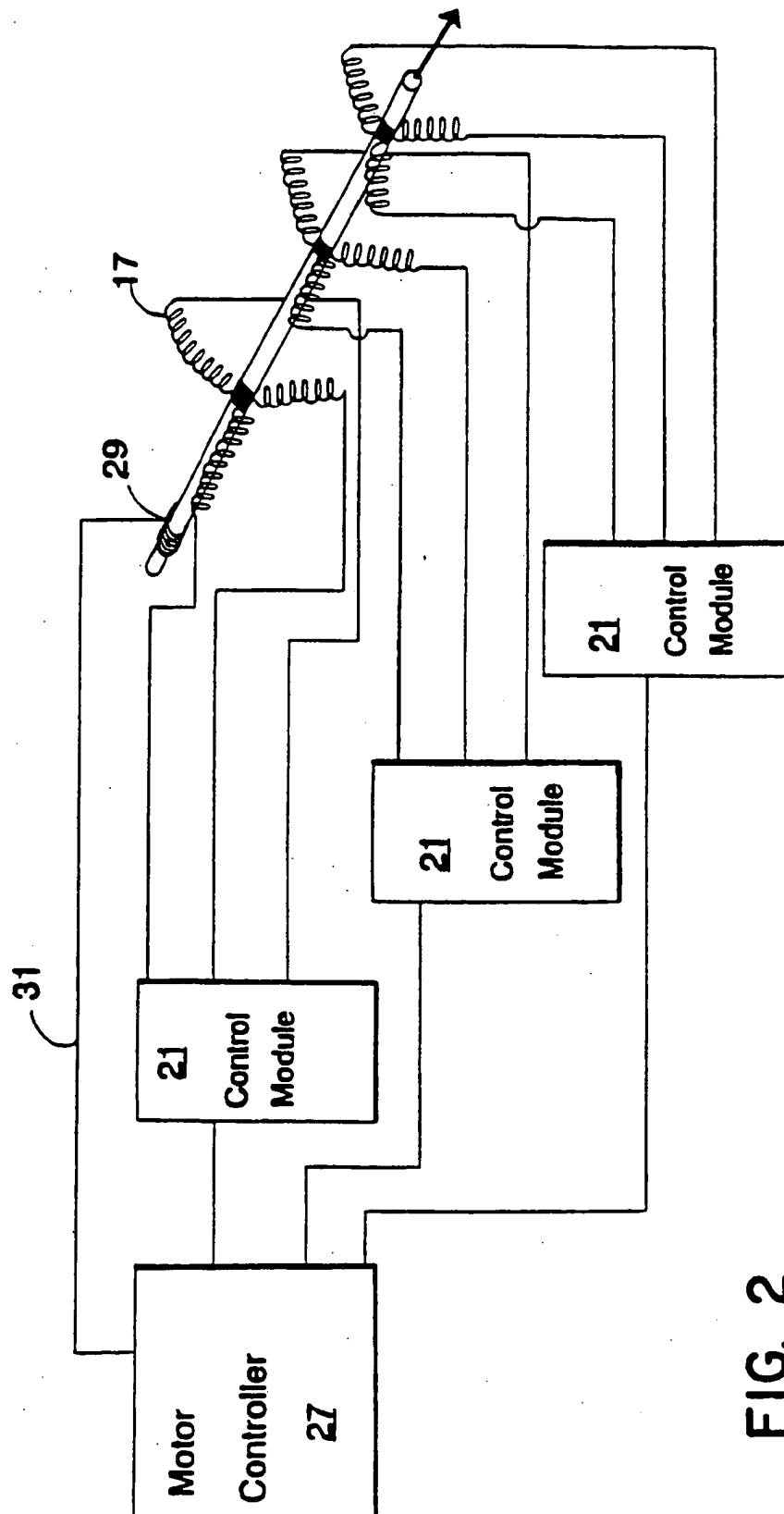


FIG. 2

## INTERNATIONAL SEARCH REPORT

Intern. Application No  
PCT/US 93/11956A. CLASSIFICATION OF SUBJECT MATTER  
IPC 5 H02K29/06 H02K16/04

According to International Patent Classification (IPC) or to both national classification and IPC

## B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)  
IPC 5 H02K

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

## C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	WO,A,84 03400 (SUNSTRAND CORPORATION) 30 August 1984 see page 5, line 21 - line 30; figures 1,2A,6 see page 8, line 25 - page 11, line 13 see page 13, line 6 - page 14, line 16 ---	1,2,4
Y	FR,A,2 493 059 (KOLLMORGEN TECHNOLOGIES) 30 April 1982 see page 4, line 23 - page 8, line 7; claim 1; figures 1,3,4 ---	1,2,4
A	US,A,3 809 990 (KUO ET AL.) 7 May 1974 abstract see column 3, line 17 - line 23; figure 8 see column 4, line 46 - column 5, line 19 -----	1-4

☐ Further documents are listed in the continuation of box C.☒ Patent family members are listed in annex.

## \* Special categories of cited documents :

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Name and mailing address of the ISA  
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NL - 2280 HV Rijswijk  
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## INTERNATIONAL SEARCH REPORT

Information on patent family members

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